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Assessment of the Present NASA Optical Metrology Capabilities and Recommendations for Establishing an In-house NASA Optical Metrology Group

Final Report

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Rationale for Establishing

an Agency-Wide Optics Metrology Group

Executive Summary

In NASA and in some aerospace companies, optics are not viewed as a concern of the quality programs, rather the optics organizations present projects with optics packages that are accepted based on the optics organization's reputation. Certainly paperwork is signed, but the quality organization generally does not have the specific optics training to understand the significance of the content of the paperwork. QA simply checks to see if all the boxes have been signed by the appropriate personnel.

Although the HST failure brought this problem to a head, little concrete action has been taken to rectify the lack of concern of most NASA QA groups about optics. This is particularly hard to understand from a QA viewpoint because for most missions, there are no backup optics, there is no way to fix most failure modes in optics and if the optics fail, this usually means the mission is a failure. Except for optics, this is the kind of scenario in which QA usually gets most heavily involved.

At first glance, there is certainly a reason for this hands-off attitude on the part of many QA organizations. Optical systems are stable devices and are not subject to many failure modes other than catastrophic ones. Even if an optical system is not working as well as it is supposed to when it goes into operation, most quality organizations are not even aware of the problem based on the data coming back from the system nor do they have an understanding of how the shortfall affects the usefulness of the data to the project scientists.

NASA is not alone in this rather hands-off approach to optics from the quality assurance standpoint; the head of QA at a quasi-governmental organization responsible for monitoring a number of very expensive and sophisticated optical systems said in so many words that his QA group did not understand optical systems and left the quality function to the optics project organizations. To illustrate the illogic of this approach, he went on to say that of course if a system had an electronic focal plane, QA would be involved with quality issues associated with the focal plane array.

There appears to be great frustration on both sides of the issue. Most QA managers know there is a problem with optics QA and have been directed by Safety and Mission Quality to take action. As a result of this, consultants have been hired to look at the problem and MSCF has a person with an optics background in the QA organization monitoring AXAF at HDOS. These are not long range solutions, however. The consultants will or have gone and the optics person does not want to make a career of QA. Further, there has been no on going commitment of funds to correct the problem.

On the other hand, many optics organizations and the people within them are uncomfortable with their dual responsibility to produce optics under great pressure from project offices and also to be held accountable for the quality of the optics. Of course, they should be accountable for the quality, but if there is no independent person outside their organization with a specific understanding of optics that the optics person can turn to if they feel there is a quality problem, this creates a great sense of frustration and serious integrity problem for the person or persons involved.

There were technician and engineering personnel involved with HST that were certain there was a problem with the primary mirror, yet there was no one sufficiently knowledgeable in optics in the NASA project monitoring organization to understand the significance of the test data. When years later it was obvious there was indeed a problem with the mirror, these people had an overwhelming sense of guilt that they had not pursued their misgivings further at the time.

This report is about a specific approach to correct these worrisome optics quality problems and the action required to provide meaningful optical metrology support by NASA for its vendors and for the scientists whose careers can often depend on the success of a mission. It is recommended that an Agency wide Optics Metrology Group (OMG) be formed under the day-to-day supervision of the Optics Branch at MSFC. It is further recommended that the OMG maintain an official liaison with Code Q so that the OMG can get the authority to take action if appropriate quality procedures are not being followed in an optics program.

The OMG would constitute about 10 people, 3-4 senior optical engineers or scientists, 3-4 optical engineers that would spend a good part of their time on-site during the manufacture of optics and 2-3 technicians to support the engineers. The OMG would be available to support optical metrology on an agency wide basis. As part of this support, the OMG would have a "stable" of the latest optical metrology instrumentation and the expertise to operate the equipment and train others in its use.

In addition, the OMG would include an Advisory Panel of outside optical metrology experts from Academia, Government Labs and possibly industry that would advise the OMG staff on the latest developments in optical metrology and would field problems of a unique or state-of-the-art nature. Another purpose of the Advisory Panel would be to keep open ties to expertise in other fields and institutions to work with the OMG.

In addition to helping monitor and support optics metrology on programs and keep current with the latest needs in metrology, the OMG would operate an "Optics QA Hotline" so that if there were ever a question in the mind of a vendor technician or engineer about some aspect of an optical system or if a project scientist were concerned about the quality of their optics, knowledgeable help would be just a phone call away. This way, if the concerned person did not get any satisfaction through regular channels, there would be an anonymous path outside of their immediate organization for a knowledgeable second opinion. Every such call to the Hot Line would require an investigation of the problem and a written report of the disposition of the inquiry.

It is fair to ask at this point, Why should such a group be set up in such an unconventional manner? Why not just institute an optics group within Code Q? There are several reasons. First, there are virtually no optics people within Code Q now and this new group would likely be outcasts and therefore ineffective. Also, relative to mechanical and electronic issues, the number of optics issues is small and it probably is not cost effective to have a strictly optics QA group.

In addition, optics is a technology that is changing very rapidly and the challenges of upcoming NASA missions is pushing the technology to the limits. Thus to keep current, the OMG will have to be doing continuous upgrading and research into new methods, not exactly the charter of a QA group. Yet if this continual upgrading does not take place, the OMG will not be effective.

In the long run, it will be much more effective to leave the OMG as a branch of the Optics community in general but with the authority through Code Q to exercise a QA function as drastic as shutting down a program if proper procedures are not followed. It is not that there have been many failures in optical systems. In fact, the optics organizations within and without NASA have done a very good job of monitoring their own work. However, when there is a quality problem in the optics area there is presently an inadequate and inappropriate response simply because the needed personnel are not available and/or do not have the authority to take the action necessary to get matters back on track.

The OMG is a relatively modest undertaking given the public awareness of optical programs and their successes. On the other hand, the OMG will provide the expertise and autonomy needed to take timely and appropriate action. Because of the Advisory Panel, the OMG will have access to an additional level of optical metrological expertise so that authoritative second opinions can be had quickly and decisions can be made expeditiously. The recommended formation of the OMG is a straightforward and easily implemented fix to a frustrating and readily apparent quality assurance problem in optics.

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I. Introduction

NASA has many programs based on optical sensing that produce pictorial output such as the Mars Orbiter and the Hubble Space Telescope. Because this output is pictorial and easy for the public to relate to, the success or failure of the project is front page news. The actual optical components that produce this pictorial image must be made and tested with extreme accuracy in order for the system to produce good images. On the other hand, the manufacture and testing of optical components is highly specialized, and uses sophisticated, not commonly employed metrology techniques.

Because of the limited manufacturing and personnel resources available for producing the heart of optical sensing systems, it is incumbent upon NASA to exercise particular diligence in insuring that these optical components are correctly made and tested. It is the purpose of this report to indicate why NASA needs to establish and fund an Optical Metrology Group (OMG) under the day-to-day supervision of the Optics branch but with authority to act in a QA role. To support the premise for the need for an OMG, this report will discuss:

*why it is essential that QA be involved in optical systems,

*that there is presently virtually no optical expertise in QA,

*the difficulties in performing optical metrology, and

*what would comprise an OMG and how it would function.

II. Background

While there has long been a concern within the NASA QA organization about problems associated with optical metrology, no one within or without NASA knew quite how to deal with the concern. The success of one optical program after another gave a false sense of security within NASA project and quality organizations. There were plenty of quality problems related to other aspects of NASA missions to worry about. In the process of dealing with those problems, no one was looking for more things to worry about.

This lack of concern came to an abrupt end in the summer of 1990 with the launch and check out of the Hubble Space Telescope. It was obvious that there was a problem but it was unimaginable that an error could have been made in the manufacture of the optics. After a thorough investigation it was found that not only had an error been made, but that it was the result of a fairly simple mechanical measurement made using optical techniques, and that there existed evidence of the error in 2 separate sets of optical test data made at the time of the final testing.

Unfortunately, the people who had the skill to interpret the optical data were either too busy to look at the data or did not want to believe what they saw. Others with a responsibility to pass judgement on the data did not have the background or skills to recognize that a problem existed with the optical data.

The report of the Allen Investigation Committee was quite clear in pointing out that even without additional tests, evidence of an error in testing existed comtemporaniously with the final figuring of the primary mirror. The report also suggested that one reason the error was not found by program monitors was that there were too few Government personnel with access to the data that had the skills and knowledge of optical testing to recognize the significance of what the data indicated.

The head of NASA Safety and Mission Quality, and a member of the Allen Committee, moved quickly to point out the need to strengthen the optical skills in the quality organization. Unfortunately, most of the managers within the quality group are not familiar with optical metrology and did not understand the special needs in this area. As a result, the NASA quality organization is not much better prepared 2 years later to detect another such problem before it is too late to fix.

The present AXAF program is not in much different shape than HST was when it was built 10 or more years ago. AXAF has a QA monitor that does have an optics background but the person in question does not have much career experience in optics, was not trained in optics metrology as a specialty and is not an expert in grazing incidence optics. Furthermore, the AXAF optical system is more complex, is required to have a higher accuracy than HST and has the same sort of programmatic pressures that contributed to the Hubble failure. The principle difference in the 2 programs is that AXAF will be tested as a finished optical system before it is flown whereas HST was not.

For all the potential problems with optical metrology on AXAF, worse is yet to come. Future NASA optical programs stretch the state-of-the-art far beyond the requirements of AXAF. The requirements become more difficult in at least 4 ways although in most cases not all at once: systems are larger, operate over greater spectral extremes, operate over wider thermal extremes and operate as interferometers rather than imaging instruments. While the optics *per se* obey the same rules in these new situations, each new requirement places a greater burden on the quality and metrology monitors because of the broader base expertise needed to understand the technology extremes.

III. The Essential Role of QA in Optics Programs

From a strategic viewpoint, optical systems are one of the first things that should concern a QA organization:

*there are generally no back up optical systems, particularly for large optical systems,

*there is usually no way to fix an optical system because the failure, if there is one, is catastrophic,

*there are generally no prototype optical systems and the real systems are too expensive to do true simulations on.

The reason that optical systems have not been much of an issue until recently is that the optics organizations within NASA and at their vendors have done a superb job policing themselves and that optical systems are very stable and do not wear out in the sense that mechanical and electrical systems do. Unfortunately this has given rise to a false sense of security.

Another not so obvious but just as serious a QA issue is the burden it places on the manufacturing organization if there is no effective QA. There is always the trade off between getting the job done (read profit or points for getting the job done) and quality. If the same organization is responsible for both and a person at a junior level (where all the real hands on work is done) feels there is a quality issue, to whom is that person to turn if there is no independent quality organization?

There were technician and engineering personnel at the time HST was built that had grave concerns about whether the primary mirror was indeed the correct shape. These people did pursue these concerns to a point within their organization but were not listened to. If there had been a knowledgeable NASA QA presence there at the time, one or more of these people could have gone to the NASA QA person and explained their concern. It would have definitely been NASA's problem to investigate at that point.

Because there were no NASA people with sufficient understanding of the tests, the NASA monitor would have been forced to go back to the optics manufacturing organization to ask if there were a problem. This could easily have cost a job or two, so no attempt was made to pursue the concern further. Now ten years later there are people at the vendor organization who feel terribly guilty that they did not do more at the time. The point here is that without a knowledgeable, independent quality organization with some real authority to bring about change, there will be a serious morale problem on the program. This is not just a NASA problem, but a quality problem in general. No company is going to make quality products if the workers do not think management is interested in quality.

The point here is that optical systems are by their nature a quality problem waiting to happen. In addition, if there is no knowledgeable, sympathetic ear when quality issues arise, the people actually doing the work will not be diligent about the quality of their own and their coworkers output.

IV. Lack of a Real Optical QA Presence at NASA

In this part of the report, we will document our findings about optical expertise within the NASA Code Q organization at those Centers involved in optical programs. We also mention several other related experiences involving QA and optics to show that the problem is not unique to NASA. These finding are based on visits to the Centers mentioned and phone conversations with the heads of QA and/or metrology at the other organizations.

At MSFC, I spoke with the head of QA about optics expertise in his group. He said in so many words that while there were over 200 people in the S & MA group there were none with an optics background and monitoring optics performance fell to the Optics Branch. As if to back up this statement, when the backup HST secondary mirror was measured at the University of Arizona in late 1990, MSFC supplied a QA person who was familiar with QA practice but had no optics experience. In fact, she admitted this was her first involvement with anything to do with optics. Marshall also supplied an optical engineer from the Optics Branch to witness the tests.

During these same tests, JPL had a charter from Code Q at NASA Headquarters to monitor the tests of the HST backup and support optics. JPL sent 2 representatives to witness the tests under this charter, one with a career of length measurement experience and the other a respected Ph.D. in Physics. Neither, however, had any optics background and seemed to have little idea what was going on until we got to the part of the tests where we mechanically measured to distance between the conjugates in the optical test. In that part of the tests, they participated fully.

The Optics Branch at MSFC has acted positively to fill in the shortfall in optics expertise, particularly as it applies to AXAF. There is now a full time consultant at HDOS who has about 30 years hands-on optics experience. There is also a MSFC optics branch optical engineer that has been assigned to the Marshall QA group to be in residence at HDOS for the duration of the AXAF program. In addition, the S & MA group has a consultant under contract to study the optics QA problem within that group.

At Goddard, I did not speak to the head of QA, but rather spent my time with the Head of the Optics Branch. While I did not get a head count, there were easily 50 people in the Optics Branch. It was clear that GSFC had extensive familiarity with optics and optical metrology in the Optics Branch and that it was the Optics Branch people who monitored and had responsibility for vendor produced optics, not the QA people at GSFC.

The same thing was true at NASA/Ames where the entire optics effort is only a handful of people. The optics head said there was no optics support in the QA group there and I can believe that from personal experience working on a refurbishment of the Kuiper Telescope. We never once saw anyone from QA at Ames, let alone someone with optics expertise.

At JPL, I talked with the Head of QA and he said right out that there was no optical expertise in his group; they did calibrations and certifications on electrical and mechanical metrology devices only. He was aware there was a large optics activity there at JPL but his group did not interact with them except for mechanical and electrical issues.

It seemed to me that the QA situation was both better and worse at JPL than at the other NASA Centers visited. JPL builds their own optical packages in house so they are both the vendor and the customer. This is a more inbred situation than at the other Centers. On the other hand, the packages they have built in the past were reasonably small so they were easy to check out for correct operation by the engineers building the hardware. However, in the future, these instrument packages are slated to get substantially larger and more complex.

The lack of optical expertise in Code Q extends to NASA Headquarters as well. During the HST investigation, an outside consultant was hired by Code Q to support Headquarters in the investigation. It is telling of the problem that the consultant hired, while very knowledgeable about QA practice and procedures, knew nothing about optics. To the consultant's credit, about half way through the investigation, he hired an optical consulting firm whose work was valuable in cross checking the results of both HDOS and the Allen Committee consultant.

The lack of optics expertise in the QA organizations of companies dealing with optics is not unique to NASA. A quasi-governmental organization responsible for the oversight of some very expensive and sophisticated optical systems is in the same situation. The Head of the QA group there said that they were involved in the mechanical and electrical aspects of the systems but did not concern themselves with the optics, that was the optics part of his organizations responsibility. He went on to say that if an electronic focal plane were involved that of course his group would then be involved.

Perhaps it is no wonder that this apparent lack of concern about optics metrology is so wide spread when even our national standards laboratory, NIST, abandoned its optical metrology program over 20 years ago. It is only in the last year that NIST has realized that optical technology is where the future lies and that it had better start anew in optical metrology.

With this assessment of the lack of optical metrology expertise both inside and outside of NASA, we will now go on to first look at some of the problems associated with doing optical metrology and then outline a program to deal with the problem within NASA. While in a certain sense, the problems associated with performing optical metrology are a little outside the scope of this report, reviewing the problems helps make the lack of NASA QA action more understandable. It is not that NASA QA has merely shrugged off the problem. The problem is substantial and it will take genuine commitment and a continued line funding to improve and help solve the problem.

V. The Difficulties of Doing Optical Metrology

This part of the report attempts to answer the question of why there is an optics metrology problem. There are many aspects to the problem, not the least of which is that optics metrology is difficult to do. This is compounded because there are relatively few engineers qualified to do the necessary work. Optics metrology deals with traditional optics and it is not perceived to be cutting edge science so not many potential candidates take up the work.

Even when the personnel problem is recognized, it is not easy to cross train engineers from other fields with basic engineering skills because there are few standards and standard methods of doing optical procedures. In addition, optics and optical metrology deals with spatial concepts in full 3-dimensions. Few engineering disciplines force people to think as rigorously in 3-dimensions as optics and thus some of the necessary concepts are more difficult to grasp.

To make things worse, as we mentioned above, the NASA optical payloads and projects are becoming ever more complex. As these payloads push the frontiers of technology, the personnel responsible for seeing that everything is right have to be skilled in ever broader aspects of technology.

The biggest problem with optical metrology, however, is one of perception. Project managers and QA personnel who are not optics oriented do not grasp how difficult the technological problems are that these projects call for. What makes this perception worse is that the computer has made the design and analysis of the optics so relatively easy that there is the assumption that the physical manufacturing is just as easy. Nothing could be farther from the truth. There is a world of difference between designing an optical system with a primary mirror accurate to a 50th of a wave and actually making and verifying that the finished mirror is indeed a 50th of a wave. Even though the optical systems are designed to perform research, in fact, the building of most sophisticated optical systems are research projects in and of themselves.

We will now look at each of these facets of the problem:

* optical metrology is difficult

* new programs have even more difficult metrology problems

* few people are qualified to do optical metrology

* it is difficult to train new people from outside the field

* few program managers understand the difficulty of making and measuring the optical hardware for their projects,

in more detail.

Optics metrology pushes the limits of metrology

A major part of the optics metrology problem is that the quantities that need measuring are so small that the only measure is the wavelength of light itself. To use the Hubble telescope as an example, the 70th of a wave rms quality level thought to have been achieved is equivalent to producing an area the size of a football field flat to 0.0001" or flat to 1/30th the diameter of a human hair. Most engineers will recognize that just measuring a single diameter accurately to 0.0001" is difficult, imagine the difficulty of measuring thousands of points over a hugh area to this accuracy.

One aspect of measuring such small dimensions that sets optical measurement aside from usual mechanical measurement practice is that in mechanical measurement, the measuring instrument is generally accurate to 10 times the tolerance of the required measurement. This means that even if there is a small error in the measuring device, the measurement itself will be well within the tolerance of the part.

When making measurements with light as is necessary with optical metrology, the required accuracy of the measurement is the same as the accuracy of the measuring instrument. In other words, the reference against which the measurement is being made is no better than the desired accuracy of the measurement. This means there is no room for any error. Any error in measurement will result in an erroneous assessment of the accuracy of the optical part under test.

Since an error of the size of the wavelength of light will significantly affect how well the optic produces images, it is clear that optics must be accurately measured to tolerances of small fractions of wavelengths. This is why it is essential to have several methods of making the same optical measurement so that the various results may be checked against one another. The point being made is that optical measurements are difficult to make and that any error in measurement will significantly and visibly affect the performance of the final optical instrument package.

New optics payloads are more challenging

We have just pointed out that optical measurements are difficult to make. However, planned optical projects present metrology problems that are much more challenging than those in the past. Systems that operate at shorter wavelengths need to be made to proportionately tighter tolerances. While the Hubble telescope that operates in the visible and near UV had to be accurate to a 70th of a wave rms to achieve the full intended performance, X-ray telescopes that operate at 100th to 1000th the wavelength of visible light must be made and measured that much more accurately. Given the current state-of-the-art, this is unrealistic and the tolerances have been backed off to sensible limits. However, the scientists involved with these projects would like the full measure of increased accuracy needed to get theoretical resolution and will push to improve technology so they can get it.

In addition to wavelength extremes, future flights will push size extremes. HST will seem like a small telescope compared with some ideas for a next generation ST, yet there will be but a small relaxation of desired accuracies of the figure. Some optical packages will operate at thermal extremes either by being very cold for their lifetimes or less cold but continuously varying temperatures. Both these environments pose untested metrology requirements yet the absolute accuracies of the optics required will still be sub-visible wavelength.

To gain a feel for the problem, it is well known that it is fairly easy to measure the length of a 1" gauge block accurately to 1 micro-inch under laboratory conditions at 20^0C. What sort of accuracy could one expect if this same measurement had to be made at 2 degrees above absolute zero? This is the kind of optical metrology problem facing SIRTF.

There are relatively few Optical Metrologists

Part of the reason that optical metrology is not a better developed art is that there are relatively few people practicing the art. This is due to a perception within the optics community. Once it was shown that lens design could be done rather rapidly on a computer, many practitioners decided that all the interesting work in optics had been done. Since lens elements and mirrors could be specified on mechanical drawings, these were then simply given to the optical shop and after some time period, out came finished optics. The leading spirits in the field went on to work in laser optics, holography and coherence theory.

Fairly august institutions such as NBS (now NIST) decided classical and applied optics were passé and shut down work in the field. Many years ago, MSFC had a very active optics program but it too was essentially shut down. Things were so bad that in the early years of the reconnaissance programs, many of the people in the industrial organizations doing the optics were amateur and professional astronomers, not professionals from schools with optical engineering departments.

Even when the Optical Sciences Center was started at the University of Arizona as an applied optics program, students and faculty soon felt that traditional optics was not where the action was. Students who were thinking of becoming lens designers and optical metrologists soon changed programs and advisors to study quantum optics, chaos and femtosecond pulses. Reality only began to set in when these students tried to get jobs and found that the traditional optics companies wanted lens designers and optical test engineers but the students had not taken these classes.

The point here is that there are not many people leaving school with degrees in applied optics. Those that are can find well paying jobs doing design work and metrology in private industry. Relatively few are taking Government jobs, particularly in quality assurance where there is an unwarranted assumption that the work is not particularly challenging, and that the quality people must clean up other people's mistakes while getting little credit for their efforts. This is not just a NASA problem but a much more pervasive one in the optics industry.

The problem of cross or on the job training

Although there are a great number of optical engineers who started out in some other field of engineering, the number seems to be decreasing. Part of the reason is that optics is somewhat difficult to pick up and is loaded with subtleties that can be very costly. In particular, large optics programs, the ones we are most interested in, require hugh investments of labor in polishing and testing. An error in interpretation of test data or poor judgment in handling an optic can cost millions of dollars in labor and schedule. Thus, amateurs tend not to be welcome when it comes to working with the hardware.

Even in the less sensitive areas like writing test procedures or designing tests, there are no standards or standard methods of performing tests. Generally, every project starts from the bottom up. This requires people who know what they are doing, not trainees from another field.

Finally, the testing of optics means determining if surfaces have the right shape. This requires thinking out problems in a full 3-dimensions. Even the most experienced optical test people have trouble working through these problems and correctly seeing the interrelationships between alignment with test instrumentation and actual figure error that someone must remove by rubbing away glass. It is daunting for the uninitiated who want to get into the field and experienced personnel tend to be skeptical of using less experienced people.

The point here is that the lack of qualified optical metrology people is not likely to be solved by retraining engineers and scientists trained in other fields. Qualified people will have to be hired at salaries that are competitive with what are being offered in private industry for similar skills. To entice these same skilled people into a quality assurance program will probably require additional incentives.

Lack of awareness of the optics metrology problem

The real problem with optics metrology is that project management and quality assurance do not understand that optics metrology is a complex field and a discipline unto itself. Thinking that optics metrology can be handled on a part time basis by people trained in making mechanical and electronic measurements is to totally underestimate the task.

Management and quality assurance concerns relative to optics should focus on these factors:

* There are seldom backup optics packages; if the optics fail or performance is substandard, mission goals suffer in direct proportion to performance degradation.

* Optics metrology by its very nature is always pushing the limits of what can be measured and thus any systematic measurement error will compromise the optic's performance in direct proportional to that error.

* The manufacture and testing of sophisticated optical systems must be thought of as the research projects they are, not as just so much hardware for which drawings are sent to the shop and finished parts come out after a reasonable waiting period. After a long history of cost and schedule slips in almost every optics program, it should be obvious by now that optics, particularly large optics such as are often the ones flown in space, are not everyday hardware.

We should also address briefly how this state of affairs came to pass, that many project and quality assurance managers are not aware of the difficulties in doing optical metrology. First of all, most project and quality managers are not optics people and do not have optics backgrounds. Rather they tend to be mechanical, and in some cases, electrical engineers. While mechanical engineers certainly are familiar with dimensional metrology, most tend to think that working to a ten thousandth of an inch is working to very tight tolerances, that this is state-of-the-art mechanical measurement. Most optical dimensional metrology is routinely done to 2 orders of magnitude tighter tolerances. Since this is "off the scale" of most mechanical engineers thinking, they mentally relegate optical metrology to some unknown "art" or "magic" and do not even make the attempt to understand what is being done.

Similarly for electrical engineers, the dimensional measurements done optically are in a totally unfamiliar realm and most managers do not take the time to try to understand the problem. Clearly, when these people who have the technical background to be able to understand the problems of optical metrology and yet do not, then it is obvious what the position is of managers who do not have a technical background. It is fruitless to expect that these non-technical people will ever understand the problem.

Another part of the problem has been created by the optics people, namely the lens designers. In the old days, lens design was done by looking up numbers in log tables. It was the most tedious possible type work and when a design was done that met spec, that was it. No lens designer was going to go back and make the design easier to manufacture or test. Thus, lens designers became known as very haughty people. Their word was unquestioned.

Now, computers mean redesigning is quite easy, but lens designers have done little to improve their aloof image. They are still treated by most managers as though their word was the last word. Because of this, managers tend to treat the whole optics discipline as something that can only be understood by optics people and leave all aspects of the problem to the optics project people. If the optics people say something will work, there is no independent look at the optics. Sometimes the optics people turn out to be merely human and the result is a Hubble.

Another source of the problem lies in the lack of optics training within most quality organizations. If a QA person is sent in to monitor an optical test or assembly and it is clear that person has no sensitivity to optics, the person will be worse than useless and will be treated as such by the trained optical personnel. The contractor personnel who are responsible for the hardware generally will let a new QA person get involved just far enough so the contractor can see what the QA persons knowledge of the hardware is.

The first time the inspector does something that indicates he or she is not familiar with what is going on (and is therefore a risk to the hardware) the inspector will be gently moved into the background. Most inspectors who are not familiar will let themselves be moved into the background because they are intim-idated by what they do not know and realize they could jeopardize the hardware.

Once the inspector has been shunted into the background, they are in no place to see what is going on and will receive little cooperation from the contractor people because they know it is just an exercise that is wasting time rather than serving some real quality function. In fact, there is no faster way to subvert the function of quality assurance than to put an inspector on the job that is unfamiliar with the hardware and techniques of assembly and measurement. In spite of the inspectors physical presence, they are serving no use and are just a nuisance to the contractor.

As optical payloads get more and more sophisticated, even the trained optics people are not that "expert". The optics people who are comfortable with normal incidence optics like ordinary telescopes are quite out of their element when it comes to grazing incidence optics. Likewise, experts who have grown up with grazing optics have no feel for tolerances and the difficulty of making and testing more traditional optics. As NASA flies a next generation of optical missions, this problem in the optics community will only get worse. If the optics experts are not able to be experts in all fields of instrumentation, who is insuring that quality issues are being looked after? A failure with a more sophisticated system will make just as big headlines as Hubble, maybe bigger because the system will have cost more and supposedly NASA has taken corrective action to prevent a recurrence of the problem.

VI. Solutions to the Optics Metrology Problem

Now that we have looked at the reasons for the lack of attention paid to optical metrology, we will turn to seeking solutions to the problem. Part of the problem lies with how fast technology is advancing and how relatively rapidly new payloads are being built and flown. This means that the limited quality assurance resources cannot keep up with the work. If the rate at which new missions were planned and flown were to slow down, there would be less problem. Because of a resource problem throughout NASA, this part of the problem will take care of itself.

It would also help if the Project Scientists were more involved in the testing and quality assurance aspects of their projects. The usual approach here is that a Project Scientist is the one who proposes the project, convinces NASA that it is worthwhile to fund, helps guide the design phase to insure the instrument is capable of achieving its goals technologically. Then NASA turns the design over to a contractor to build the instrument. The next time the Project Scientist really gets involved is when data starts coming from the instrument and there is something to analyze and perhaps a new discovery to announce.

The Project Scientist often has little involvement in seeing that his instrument actually works or has been sufficiently checked out before it leaves the ground. This is somewhat understandable. It is much more exciting and newsworthy to conceive of a project and design the hardware than it is to go through the check out and testing. That phase is tedious and there is no glory. On the other hand, this test phase is essential to project success and the Project Scientist should make a commitment to NASA to be involved in this phase of the project or not have the project funded in the first place.

Establishment of an Agency-wide Optics Metrology Group

The much more immediate part of the solution to the optics metrology problem is the establishment of a NASA Agency-wide Optics Metrology Group (OMG) to monitor the optical quality aspects of optical payloads. Setting up such an OMG would improve the optics metrology problem in several ways simultaneously by;

1) Outwardly recognizing the importance of optical metrology and quality assurance to mission success

2) Providing NASA with a group of specifically trained optical metrology personnel to monitor optical payload manufacture

3) Providing the NASA quality organizations with a means of

training other quality people in how to be sensitive to optics

4) Providing NASA project personnel with access to the latest sources of optical metrology technology from sources both inside and outside NASA.

After first describing the structure of the proposed OMG, we will then show how the OMG would improve the status of optical metrology within NASA. It is proposed that the OMG be composed of 3 to 4 senior level optical scientists, physicists or engineers, 3 to 4 optical engineers with degrees in the field and several years experience to serve as field engineers and/or optical project monitors and 1 to 2 optical technicians to support the scientists and engineers.

In addition to these roughly 10 NASA personnel, another essential part of the OMG would be an Advisory Panel of about a dozen optical engineers and metrologists from other NASA Agencies, Government Laboratories, Universities and possibly industry. It is expected that the Advisory Panel would meet twice a year to first come up with their mutual understanding of the current state-of-the-art and then to brief the staff of the OMG as well as take questions from them on specific current problems. Individual members of the Advisory panel would also be available for specific questions at any time. If there were short term, specific optical metrology problems for which none of the OMG personnel were familiar, outside contractors might be hired temporarily to address the particular problem.

It is proposed that the OMG and associated labs be located at MSFC and take immediate, day-to-day direction from there. Some personnel of the OMG such as the field engineers might well be associated with other Centers. As the OMG is to be an Agency wide group, ultimate direction in terms of project priorities would come from NASA Headquarters and these priorities would change as the demands of various projects change. In addition, it is proposed that the OMG have direct authority to act for QA in those instances where optics quality procedures are not being handled correctly or if there is an issue that concerns the final quality of the optics.

The Functions of the Optics Metrology Group

The functions of the OMG would be several and will now be described. The OMG would provide:

1) On-site qualified optics metrology oversight for projects

2) Expert, problem specific support for the field engineers

3) Training for QA personnel in sensitivity to optics

4) Operate an optics quality "Hot Line" for vendor personnel

5) A National resource of references to optical expertise

6) Hands-on commercial optical test equipment evaluation

7) A library of optical standards and standard test procedures.

We will now look at each of these functions in detail. The on-site optics metrology support would be provided by the optical field engineers. It is expected that because of their training they will have a broad but somewhat shallow optics background. The broad background will permit them to monitor a variety of optical metrology problems associated with the specific hardware. When problems arise that are beyond their own experience, the senior scientists and engineers will be available to go on-site on a temporary basis until the problem is resolved. Members of the Advisory Panel may also be called upon and/or the talents of other Government Agencies or Universities.

The importance of the OMG having, or having ready access to, Quality Assurance authority is apparent here. Presumably, with the talents of the Advisory Panel personnel, the OMG will have the opinions of the best optical metrology experts in the country available. Since these talents are not (or are not expected to be) resident in the S & MA organization itself, there must be a mechanism in place to rapidly transfer that authority to the OMG where there is an optics issue in question.

Program management should not worry too much about having their programs interrupted because with the greater oversight from the OMG, problems are less likely to come up. Secondly, if there is a problem, the talent available in the OMG and on the Advisory Panel should be able to come to a quick method to resolve the problem.

A combination of the currently unassigned field engineers and senior engineers would run training programs for non-optical QA personnel with the idea, not of turning these people into optical engineers but rather, of helping to sensitize these people to the peculiarities of optics. QA people who are unfamiliar with optics can be a liability to a program by either causing damage to the optics or by being so afraid of causing damage that they are not doing the job of monitoring that they are supposed to be doing. This training program would help the non-optics people understand what is different about optics, how to exercise caution around and when handling optics and what subtle but important aspects of optics will possibly affect their ultimate function.

The OMG would operate an "Optics Metrology Hotline" so that if there were ever a question in the mind of a vendor technician, optical engineer or even a NASA engineer about some aspect of an optical system or if a project scientist were concerned about the quality of their optics, knowledgeable and independent help could be had with a single phone call.

The idea of the Hot Line would make it clear that there was a clear NASA management concern about optics quality and that anyone with misgivings about some aspect of a job they were working on could call for advice without being subject to pressures from immediate supervisors to just "get on with the job". It would be the policy of the OMG to document every such call, make a written report on the result of the investigation into the call and let the caller know what the disposition of the matter had been. Again, if the concern is demonstrated to have a major impact on the quality of the optics,the OMG could ask QA to stop work until the problem is resolved.

The senior OMG staff would be expected to put together a data base of all important sources of optical expertise within NASA and other National resources and keep this database up to date. The database will not only be for NASA use but would be available as a National tool. This database will contain Government, University and industry sources of optics expertise and may include non-US sources as well.

Another function of the OMG senior staff would be to purchase and evaluate commercially available optical metrology hardware and software. This function would serve several purposes, the most obvious of which is to be familiar with new test equipment and be in a knowledgeable position to make recommendations for specific projects. A less obvious but equally important aspect is that to stay current in any field requires constant practice in that field. By having and using the newest test equipment, members of the OMG senior staff will keep their own skills current and be able to advise on the best ways of handling particular metrology problems because they have had recent experience.

Another aspect of the data base would be to prepare and catalog optical test procedures. While the electrical and mechanical metrologists have physical standards they can go back to for calibration purposes, the small magnitudes of the errors optical metrologists are looking for make this impractical. Instead, optical metrology equipment is usually self calibrated or is calibrated as part of making a measurement. Procedures for doing this calibration can effectively serve as the optical equivalent of physical standards if the procedures are well worked out and easy to follow in practice. Of course, where it is appropriate to have physical standards for certain optical properties, the OMG would help maintain and calibrate these standards.

As instruments in general are being driven by more and more sophisticated software, staying current with the software and understanding the use of the software is very important. Part of the function of the OMG would be to determine if the software supplied with the test equipment does what is expected in the way of analyzing data and does so in a way that is free of systematic errors or at least warns how to avoid the systematic errors.

Interactions of the OMG within NASA

Because the OMG would be set up as an Agency-wide group, we will look at how the Group would be expected to interact within the various Centers having optical programs. For one, the senior staff would be available to work and consult for all the Centers, not just Marshall. Likewise, the field engineers whose responsibility it would be to monitor the optical aspects of projects, would be available to perform this function independent of which Center were running the program.

Of course, the databases of resources and test methods would be available to all Centers as would test equipment product evaluations prepared by the senior OMG staff. The databases would include NASA experts on optical metrology at all Centers, details of test equipment availability and laboratory facilities. Off-site test equipment and facilities would also be listed with contacts so test equipment use could be maximized.

The OMG would provide on-site optics metrology expertise for projects from all Centers. The lead role here would be the field engineers who would stay with the project from inception to final test and shipment. They would be backed up by the senior staff that would normally be resident at MSFC. The senior staff would be available for limited duration stays at contractors during unusual metrology problems. Members of the Advisory Panel would also be available for help on specific problems. If the immediate problem fell outside the expertise of the OMG and its Advisors, the OMG would have the authority to hire outside contractors for limited periods to help with specific metrology problems.

Interaction of the OMG Outside of NASA

Because of the limited optics metrology expertise nationally and the ever widening breadth of optical technology, it will be impossible for NASA to cover all the technological specialties in-house. Thus the OMG would be set up from the start with the idea of relying on centers of excellence in optical metrology outside of NASA to fill in the gaps where necessary. Another aspect of this interaction would be to coordinate studies in optical metrology. It makes no sense for several Federal agencies to all be studying the same problem. The OMG will help encourage coordination in these studies and the sharing of research results.

One of the obvious centers outside NASA would be NIST because of their charter as a metrology institution. As we have already stated, NIST is just now getting back into optical metrology in areas most useful to NASA. However, they have had on-going programs in areas that are of definite interest to NASA optical projects. There is well developed expertise in surface finish and in interferometric length measurement.

In addition, the Precision Engineering Metrology group at NIST has an interest in supporting NASA and has said they would be interested in negotiating some type of basic ordering agreement to help with optical metrology problems. One area of particular interest at NIST is in the absolute calibration of optical reference surfaces and interferometers. This capability will be of increasing interest to NASA to support future projects.

National Laboratories and military bases are another area where the OMG would be expected to set up liaisons. For example, LLNL has a 2 m diamond turning machine that can be used as a highly precise coordinate measuring machine. Oak Ridge National Laboratories similarly have very sophisticated mechanical metrology capabilities, some of it sufficiently good that it can be used as either a prime measuring capability or as a backup, cross check capability.

Other examples of test facilities of potential use to NASA programs are cryo-vacuum chambers at both Edwards and Griffiss Air Force Bases. One has a vertical chamber and the other a horizontal one that could be used in conjunction with optical testing on SIRTF. Newark AFB in Ohio probably has the best angular metrology in the country while the Air Force Phillips Lab is well set up for IR simulation work and materials studies. These types of facilities would be carefully evaluated and cataloged as part of the OMG database of National capabilities. They would include personnel, test equipment and laboratory space.

Another important area of outside expertise is resident at Universities, not so much the actual test facilities and equipment but the experts who are busy developing new approaches to optical metrology. The most notable of these is the University of Arizona where work is on-going at the Optical Sciences Center in interferometry in general, at the Steward Observatory Mirror Laboratory where they are testing large, fast optics and at the Lunar and Planetary Laboratory where IR imaging and spectroscopy is going on.

Of course, the Astronomy programs at Cal Tech and UC Berkeley have applicability to systems such as LDR while at the Advanced Light Source at Berkeley, their work in the testing of synchrotron optics is applicable to X-ray telescope optics. JPL is already working closely with the Cal Tech Physics Department on the Gravity Wave experiment. The problems for doing long baseline interferometry are almost the same as for gravity waves except for the lack of gravity in space. Again these test programs must be cataloged, facilities categorized and test methods studied. The facility associated with these major programs are all potential experts in various aspects of optical metrology.

The OMG Advisory Panel will also play an important role in keeping the OMG in touch with optical metrology work outside NASA. Because these people on the Panel will be associated largely with institutions outside of NASA, it will be only natural that they encourage liaisons between the OMG and their institutions or other groups they may be working with on similar problems.

One of the potentially more fruitful areas of interaction lies with industry. Here NASA must make their optical metrology needs known, but NASA can lend encouragement to potential commercial products and make suggestions for software upgrades. Industry can in turn offer to use NASA installations as Beta test sites for new changes and additions to their line. All this may require less of an adversarial attitude than is often present in industry/Government relationships but there must be a new understanding that Government and industry are not enemies.

VII. Conclusion

In this report, we have started by indicating that the first real appreciation for the problem of optical metrology within NASA programs started with the Hubble failure. At the time there was a genuine attempt to find a solution to the problem. However, the people responsible for the solution had backgrounds so different from those needed to tackle the change that nothing much substantive has happened in the last 2 years. It was not for lack of effort but from a lack of familiarity with how to approach the optical metrology problem.

This report is an attempt to give further background into the problem, to explain why optical metrology is so vital to NASA programs that involve optical sensors and how the problem might be solved by establishing an Optics Metrology Group within the Optics Branch at MSFC. The report gives the background and technical rationale for taking this action.

The essential role of an organization with an optics metrology background and the authority to act in a quality assurance mode is explained. The NASA S & MA Group performs this function in the mechanical and electrical technology areas but there is no similar technically knowledgeable support for optics programs within the QA program. The importance of this support has been recognized and this report outlines an approach to solving the problem within the practical constraints of the relatively small optics presence at NASA.

It is proposed that an Optics Metrology Group (OMG) be established as part of the Optics Branch at MSFC. The talents and expertise of the OMG would be available to all the NASA Centers with optical programs. The OMG would take day-to-day direction from MSFC but would have a direct line to QA authority if a quality problem arose that needed quick action. The OMG would also have an Advisory Panel of about a dozen optical metrology experts from outside NASA that would foster liaison with other Government, academic and industrial organizations involved in optical metrology. The Advisory Panel would help with technology transfer both into and out of NASA, and help avoid reinventing solutions already in use elsewhere.

The report explains why the OMG should be set up within the Optics Branch rather than within the Quality organization and why the OMG needs to have authority stemming from a close association with the quality organization. This proposed solution will serve the NASA optics community Agency-wide, provide a much needed quality input for the NASA optics programs and help improve optics metrology in general.

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This Final Report indicates when it was first recognized that there was a deficiency in NASA optical metrology oversight capability, why this deficiency existed unnoticed for so long and a proposal for correcting the problem. It is explained why this optical metrology oversight is so critical to program success and at the same time, why it is difficult to establish due to the nature of the technology. The solution proposed is the establishment of an Optics Metrology Group within the NASA/MSFC Optics Branch with a line of authority from NASA S & MA.

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